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# HIGH RESOLUTION X-RAY EXPLORER (HIREX)

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# The High Resolution X-ray Explorer

Progress Report - NAG5-3878

## 1. Overview

SAO is involved in a study to determine the feasibility of building an orbiting telescope capable of resolving 7 km structure on the Sun. In order to achieve the required imaging the telescope must have a resolution 0.01 arcsec. This fact challenges the state of the art of orbiting telescopes in several areas:
Mirror Figuring
Optical Metrology
Optical Mounting
Mirror Figure Control
System Alignment
Optical Stability
Observatory Pointing
Image Stability Image Stability

The telescope design concept is based on a 0.6m Gregorian-style telescope with a 240 meter effective focal length. This is achieved with 2 mirrors supported at opposite ends of a 35m space-deployable boom. The telescope mirrors are coated with multilayers designed to reflect a broad XUV passband. A third, small mirror, near the focal plane performs the function of selecting the narrow band that is finally imaged. Image stabilization to the 0.005 arcsec level is achieved by active control of the secondary mirror.

The primary mirror is held unadjustably to the spacecraft, its pointing set by the spacecraft orientation. The secondary mirror is mounted on a 6-axis stage that permits its position to be changed to align the telescope in space. The stage is intended for intermittent adjustment, both because of its speed of travel, and the TBD alignment procedure. The third mirror is called the TXI (Tuneable X-ray Imager). It is mounted on a gimbal that permits it to be tipped over a 60 degree degree degree degree degree degree degree degree range, selecting between the individual wavelengths in the initial bandpass. It can also rotated completely out of the way to allow the full, broadband EUV flux to strike the focal plane.

Finally, the focal plane assembly is designed to rotate on the outer edge of a circle centered on the TXI mirror rotation axis. This permits the focal plane to move to the location that the TXI redirects the light once it has been set to a given wavelength response.

The Engineering Study is divided into the following areas:

Mirror Fabrication and Metrology

Optical Layout- Trade Study between On-axis and Off-axis

Overall System Design

Pointing Control/Image Stabilization

The observational goals of the mission are described in the Mission Requirements document. The work is being performed to the requirements called out in the Science Requirements document.

## 2. MISSION REQUIREMENTS

MISSION GOALS:

To use the Sun as a laboratory to understand interactions of magnetic fields and hot plasmas on spatial scales approaching plasma and kinetic scale lengths. To understand the formation of the solar corona. To understand the initiation and evolution of solar flares.

SCIENCE OBSERVATIONS:

To achieve the mission goals requires imaging of the Solar corona with a spatial resolution of 0.01" or better at high time resolutions of order a few seconds. To interpret the observations of 0.01" resolution, a full-disk observation of the Sun at the same wavelengths is required.

INSTRUMENT COMPLEMENT:

Two solar-pointing EUV telescopes with CCD detectors.

MISSION REQUIREMENTS:

MR-1. Lifetime: 2 year design life, 5 year consumables

MR-2. Launch date: 2002-2003

MR-3. Launch Site: TBD

MR-4. Orbit: Sun/Earth L1 halo orbit (1.5 million km from Earth, semi-diameters approx. 300K km x 600K km elliptical orbit). No requirement on orbit determination at this time. Period: approx. 6 months

MR-5. Ground Station: dedicated 11m dish. Backup sites: DSN, shared WOTS 11m.

Mission Characteristics:

MC-1. Launch Vehicle: Delta-II 7929H (Med-Lite may be a requirement, ie., a Delta 7329, which has much reduced capabilities)

MC-2. Instruments: 2 co-aligned soft x-ray/EUV high resolution imaging telescopes. Large format backside thinned CCDs.

Rationale for Mission Requirements:

MR-1:

MR-2: A launch in 2002-2003 will achieve parallel observations with Solar-B and potentially with Solar Probe. Such observations would enhance the science return of HIREX.

MR-3:

MR-4: A L1 halo orbit is required to achieve the stable environment required for the ultra-high resolution requirements of the science.

MR-5: A dedicated system is required to achieve the telemetry requirements of the science.

## 3. HIREX Science Requirements Document

1.1 Image quality:

FD-TXI: The optical train (primary mirror, secondary mirror, TXI flat mirrors, entrance aperture and focal plane filters) shall have a 90% encircled energy of < 2" and a FWHM n.t.e. TBD".

HR-TXI: The optical train (primary mirror, secondary mirror, TXI flat mirrors, entrance aperture and focal plane filters) shall have a 90% encircled energy of ¡0.02" and a FWHM n.t.e. TBD".

(NB: Pixel sizes for the instruments are approximately 0.5" and 0.01" respectively)

1.2 Multilayer coatings:

1.2.1 Bandpass: Primary and secondary mirrors to have broad-band (170-220A, TBR) coatings.

1.2.2 Reflectivity: Primary and secondary mirrors to have a peak reflectivity > 25% at TBD lambda.

1.2.3 Uniformity:

1.2.4 TXI mirrors to have..??

1.3 Spectroscopy:

1.3.1 Mechanism Times (all include settling times):

1.3.1.1 Changeover time, TXI-broadband: 5 minute (TBR), including settling

1.3.1.2 TXI small-lambda (0.5A  0.045 radians) motions: 1 second (TBR)

1.3.1.3 TXI large-lambda (from any lambda to any other, approx. 0.15rad): 5 seconds (TBR)

1.3.2 Mechanism Accuracy: TXI smallest steps are 0.1A ( 0.009rad).

1.3.3 Mechanism Repeatability: TXI lambda repeatablity to within 0.1A.

1.3.4 Mechanism range: TXI range is 170-220A (TBR)  8degrees, or 0.15 rads

1.3.5 Mechanism directionality: TXI must be capable of slewing up and down in wavelength.

1.4 Telescope co-alignments (see note below on required offsets):

FD-TXI to MR-TXI: 100" on orbit

MR-TXI to HR-TXI: 10" on orbit

Magnetograph to FD-TXI: 30" [TBR] on orbit

Offsets: The telescopes are not strictly co-aligned. There is an offset imposed by the requirement that the gaps in the CCDs caused by butting them do not overlap. Thus, the MR-TXI CCD image falls 250 +/- 100 FD-TXI pixels above the FD-TXI butt line. Likewise, the HR-TXI image falls 200+/- 200 MR-TXI pixels above the MR-TXI butt line.

1.5 Optical Alignments:

1.5.1: Each telescope's optical system must be capable of achieving final alignment in orbit consistent with the required image quality as defined in 1.1.

1.6 Focus Requirements:

1.6.1: Each telescope's optical system must be capable of achieving final focus in orbit consistent with the required image quality as defined in 1.1. Both coarse and fine focus must be provided for.

2. FILTERS:

2.1 Focal Plane Filters: Shall transmit not less than 80x-ray flux, over the range of 170–220A.

3. LIGHT REJECTION

4.1 Visible light rejection at the focal plane: variable from 10*4 to 10*14 by using different focal plane filter combinations (requires 2 filter wheels with at least one open position on each).

4. EXTENDABLE BENCH:

4.1 The bench must be capable of extending to a final length of 30m, and must be capable of fitting inside a Delta-2 shroud at launch. The bench must be of sufficient stiffness to enable the focus and alignment of the telescopes to be maintained over periods of not less than 30 days.

5. CCD REQUIREMENTS

5.1 Minimum integration time: 0.1s

5.2 Maximum integration time: 200s

5.3 Detector size: 4Kx4K (or 2Kx4K, buttable)

5.4 Read noise requirement: TBD

5.5 Dark count requirement: TBD

5.6 Simultaneous start times: Any combination of science CCDs must be capable of simultaneous start times (to within 0.1 TBR seconds).

6. CALIBRATIONS

6.1 Ground Calibrations:

6.2 In-flight Calibrations:

6.2.1 CCD Dark frames

6.2.2 CCD Flat fields

6.2.3 Throughput vs. time

6.2.3.1 Filter throughput vs. time

6.2.3.2 Mirror reflectivity vs. time

6.2.3.3 CCD sensitivity vs. time

7. ISPI REQUIREMENTS

8. MAGNETOGRAPH REQUIREMENTS

9. POINTING REQUIREMENTS:

9.1 Absolute knowledge:

9.2 Relative:

9.3 Max. offset from Sun Center:

9.4 Separate Telescope Offsets: there are no requirements that the three telescopes be capable of viewing different FOVS.

9.5 Focal plane must be capable of following a feature at the solar equator for exposures between 1–200 seconds.

(2km/sec at solar eq = 0.3 pixel/second in HR-TXI, and 0.003 pixel/second in FD-TXI, assuming 12 micron pixels).

10. TIMING REQUIREMENTS:

10.1 Absolute timing: to within 1 TBR second

10.2 Relative timing: to within 0.1 TBR second

B. HIREX DERIVED ENGINEERING REQUIREMENTS

C. HIREX ENGINEERING DESIGN DRIVERS

1. All optics must be easily accessible/replaceable. Replacement includes alignment/focus.

2. Weight reduction is a primary consideration.

## 4. HIREX Mirror Fabrication and Metrology

The HIREX mirror fabrication and metrology study is being performed in several locations. We are working with Hughes Danbury Optical Systems (HDOS), Bauer Assoc., and Goddard Space Flight Center (GSFC) to completely review the state-of-the-art of mirror fabrication and metrology.

Fabrication:

The underlying plan is to follow the mirror requirements that have been laid out by the XUV lithography industry in their goal of achieving the next generation of computer chip manufacturing equipment. Their requirements closely match what our initial estimates suggest that we need. Bauer Associates has begun working on a complete mirror system specification, and a determination of the surface figure precision and optical positioning tolerance. The initial on–axis design, based on spherical optical components, initial optical design was laid out by Leon Golub and analyzed by Andrew Szentgyorgyi. The current off-axis baseline design consists of an aspheric primary mirror and a spherical secondary mirror, a change made to improve image quality and release valuable error budget to other portions of the system design.

This more complex aspherical design was established by Bauer Associates. HDOS will be examining the feasibility of fabricating optics of this quality, size and focal length.

Metrology:

Metrology methods are being examined here and at Bauer Assoc. Bauer will be examining the feasibility of various metrology techniques, both exisiting and new, for use in the various phases of the mirror processing: fabrication, coating and mounting. We (SAO) are looking at the requirements placed on the mirror support during the metrology process to ensure that un-accounted for support or gravitationally induced deflections are not misinterpreted as real figure errors and their negative polished into the mirror. We are also looking at the requirements placed on the mirror support during operations to ensure that the mirror support does not distort the primary mirror.

## 5. HIREX Optical Layout Trade Study

The HIREX mission study is examining various optical configurations to determine a design approach with a high likelihood of mission success. As part of this process we are comparing a telescope designed around on-axis optics to one with off-axis optics. The trade off is a complex one with many pros and cons on either side. Because of this complexity, it has been decided that the comparison should be explicitly laid out.

Basic Designs:

The two design that are being compared are described.

On-Axis:

The on-axis design is a standard gregorian with a field stop at the prime focus. The primary mirror is supported through its center hole with a TRACE-like mount. The mount seats consist of a similar epoxy/siltex casting held on invar clamping components. The details have been refined from the TRACE design because of the extreme figure requirements that the HIREX mission imposes.

The secondary is also held on axis. It is mounted on a 6 axis adjustment stage and the combination is suspended from a spider. The field stop is held either by another spider or a cantilever from the secondary assembly itself.

Off-Axis:

The off-axis design (Fig. 1) was proposed to alleviate the thermal problems that the secondary penumbra induces on the primary. The primary has no central holes and is supported by a set of tangential flexures. The flexures will be sized to balance the need for extremely low figure error with the modest mirror dynamic stability requirement.

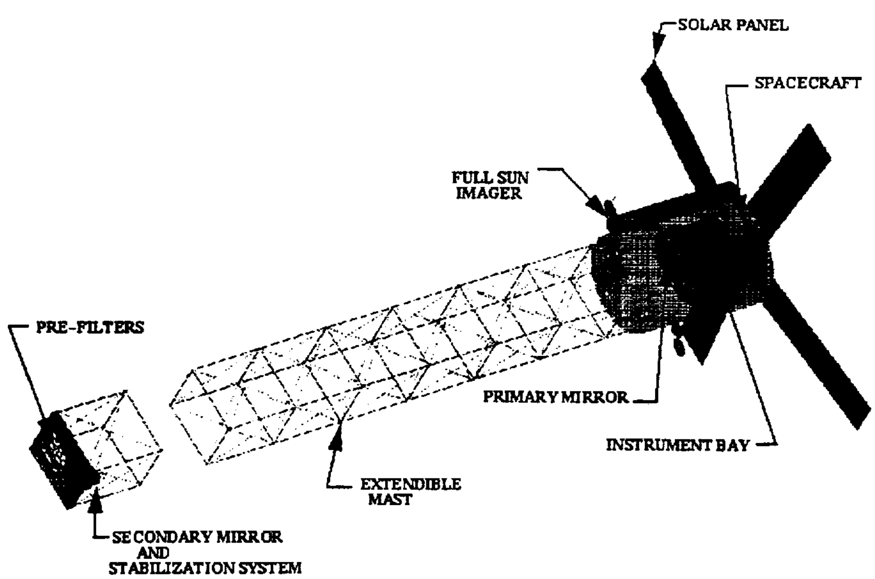


Figure 1. The HRS Explorer Off-Axis Design

The secondary is most likely on axis, mounted in the same manner as the on-axis system. However the secondary assembly will be supported on a solid plate mounted in one corner of the telescope truss. The field stop, again at the prime focus, would be supported in a way similar to that described above.

**Trade Study:**

On-Axis Design:

Clear Benefits:

Well studied

Clearly defined mounting system that can achieve the required figure requirements

Clear Drawbacks:

Primary always in partial, non-uniform illumination.

Illumination varies as the telescope is pointed to different positions on the sun

Diffraction from the secondary spider, primary mounting hole, and field stop

Off-Axis Design:

Clear Benefits:

Primary illumination is constant and uniform.

Primary illumination is unchanging with pointing orientation.

Well studied in other telescope designs.

No diffraction sources aside from the field stop

Clear Drawbacks:

Unknown if support can achieve high figure requirement.

Head to Head Trades:

Thermally induced mirror shape change:

The effect of the nonuniform illumination of the on-axis system has to be compared to the thermal shape changes on an off-axis mirror. The essence of this distinction is that the non-uniform illumination, both in time and across the mirror may induce undesirable figure changes. On the other hand the off-axis mirror is supported about the periphery of the substrate, which is not symmetric with the surface figure. In spite of the apparent symmetry of the support the shape change will not be symmetric with the true figure.

Support Design:

The mirror support is a large issue, second only to the ability to generate the mirrors themselves. The study has progressed to the point where we are able to predict a successful mount design for the on-axis case. Due to the symmetrical layout of the mirror and the mount there are straightforward approaches to reducing the surface effects of clamping and compensating for those that we can not remove. On the other hand the mount induced surface effects of an off-axis system are unknown but most likely non-compensatable. These must be determined, reduced where need be, and finally compensated for.

Mirror Fabrication:

The on-axis mirror has a hole in it, the off-axis mirror does not. We must compare the relative difficulty of polishing around the central hole versus generating an off axis, non-spherical shape.

Metrology:

Metrology is a problem for this project in any event. We must compare the available metrology systems for on-axis and off-axis systems, and their chances of achieving the required resolution.

Industrial Comparison:

We have selected a standard of mirror performance that is being pursued by the electronics industry. We have tailored our specification to look as close to those proposed for XUV lithography as possible. The HIREX baseline design has a 0.6m mirror and a roughly 6A figure error tolerance to match the industrial goal. The HIREX mirror is going to have a much longer focal length, 35m vs 2-5m, and it may be either on-axis or off-axis versus the industrial goal of an off-axis mirror. We must determine if the fact that the baseline HIREX design becomes off-axis improves our argument that we are building a system similar to that being addressed by industry or is the focal length distinction such a large difference that all other considerations are minor.

Secondary Support:

There are real differences in the inherent stability between the secondary assembly support in the on-axis design and that in the off-axis case. These effects have to be examined.

Focal Plane Issues:

The trade-offs at the focal plane are unclear. By going with an off-axis design we open up considerable latitude in the axial position of the focal plane at the possible expense of the light rejection and thermal control of the focal plane. Aside from these possible issues the focal planes are nearly identical.

## 6. HIREX Overall System Design

Overview:

Competing HIREX designs have been carried out for both an on-axis and off-axis telescope system. Some of the key subassemblies discussed below differ for the two systems. Where this is the case each design is discussed. At present the off-axis design is the baseline.

The HIREX system design has centered on several key areas:

Mirror
Thermal Analysis
Off-Axis mount
On-axis mount
TXI design,
Instrument Design,
Off-Axis Instrument Design
On-Axis Instrument Design
Image Stabilization System,
Secondary Mirror and Support System,
Boom,
Field Stop Support System,
Pre-filters,
Spacecraft and Launch Issues.

## 7. HIREX Pointing Control and Image Stabilization

Overview:

The stated HIREX imaging goal is resolution at the 0.01 arcsec level. There are many components that affect the achievement of this goal, one of the most basic is the stability of the image on the focal plane during an observation. Responsibility for achieving this goal is distributed between the instrument and the spacecraft. The present plan is to permit the spacecraft up to 5 arcsec of pointing error. Image motion within that band is removed by a tip/tilt servo system on the secondary. The primary image motion sensor is a set of correlating image trackers mounted at the focal plane around the science CCD.

Models:

In order to determine the likely image stability on orbit a dynamics simulation of a full spacecraft model has been made. In order to construct this model, several intermediate models and modeling systems have been used. The dynamics model was constructed in AUTOSIM, a dynamics modeling software package written at the University of Michigan Transportation Department. This package takes a description of the geometric and constrain layout of the system and produces a set of equations describing the system dynamics. The output can be in a number of forms, we have selected an output in MATLAB form. We have used SDRC IDEAS, both solids modeling and FEA to determine the system inertial and elastic properties. Finally the dynamics model was placed within a Simulink model (a block diagram modeling system operating under MATLAB) where all the control system design and simulation work was done.

The model includes:

The first 2 boom modes,

The TXI, and its movement freedom,

The angular adjustablity of the secondary,

The filter wheel, and its movement freedom,

3 mutually orthogonal reaction wheels and related noise,

The image stability system and associated control.

Where possible real world effects like the averaging nature of the correlating star tracker and its sample and hold operation have been included. In later runs we will examine the effects of limited resolution in both the image measurement and in the secondary position control.

Preliminary Results:

The preliminary results are promising. The graphs below show aspects of the predicted system behavior in response to a candidate observatory repointing. The spacecraft is commanded to change its line of sight by 120 arcsec over a period of 80 seconds. The pointing path and rate are specified. The resulting image motion is shown in Figure 2.

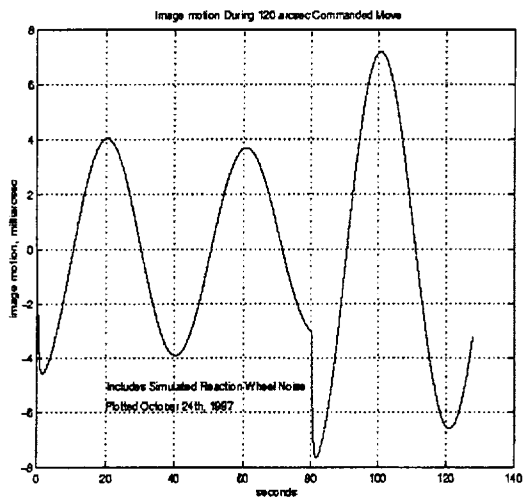


Figure 2. Image motion During 120 arcsec move

Figure 2 shows that the image remains within the stability requirements even during this large system repointing. The spike at 80 seconds results from the details of the pointing command at the end of the move. Specifically the pointing rate command is set to zero just as the spacecraft overshoots its intended target, this results in a large reaction torque. The deflection is the result of fact that the secondary is out on the end of the swinging boom and thus has an applied inertia torque. This can be overcome with a more complex control law.

The spacecraft pointing performance is shown in Figure 3:

The spacecraft, at least the instrument bay, follows the pointing command quite well. However as Figure 4 shows that the boom has a much larger amplitude.

Note that this graph shows the deflection of the boom, the scale on the left hand side of the graph, and the linear decenter of the secondary at the right. Though boom angle

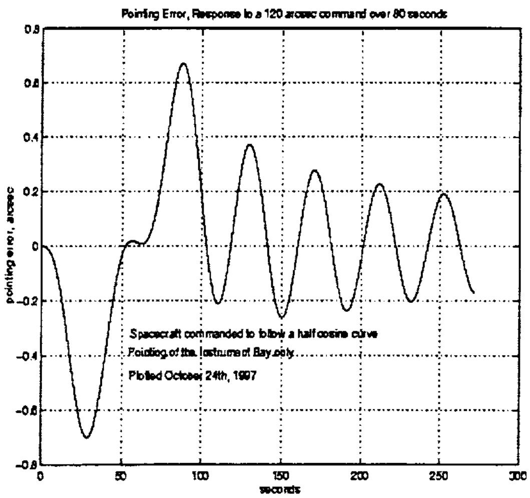


Figure 3. Spacecraft Pointing Error During 120 arcsec Maneuver

and secondary decenter are not strictly related by a constant ratio, it is close enough for preliminary performance determination. ati

Finally Figure 5 shows the reaction torque required to make the simulated move:

It is clear, that at least for the simulated move the reaction torque requirements are modest and lie within the capability of available reaction wheels.

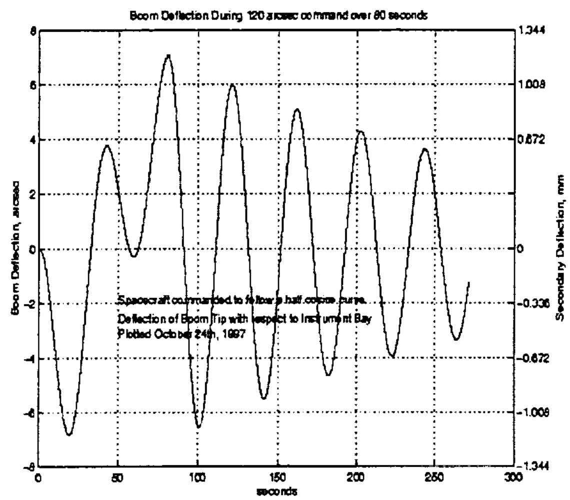


Figure 4. Boom Deflection in Response to a 120 arcsec Maneuver

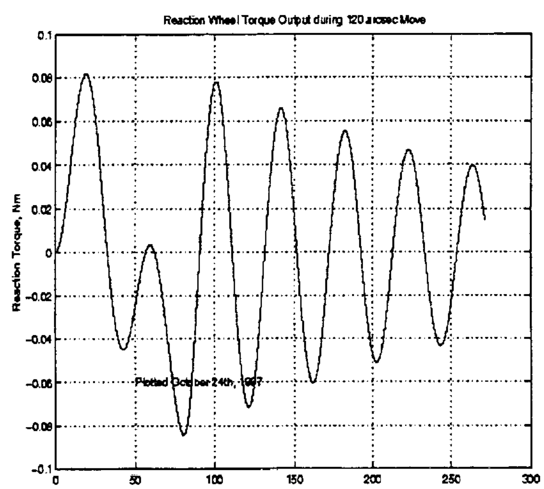


Figure 5. The Commanded Torque During the 120 arcsec Maneuver